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16. ABSTRACT

A new method for evaluating soil and calculating the thickness of pavement base required over any type of soil to support highway traffic or airplane wheel loads carried on pneumatic tires is under study by the California Division of Highways. A relatively simple design chart has been developed (Fig. 2) that makes use of certain physical characteristics of the basement soil and the pavement or pavement base as well as the surface loading. The theory on which the chart is based has been substantiated by results obtained on highway and airport track.

This design procedure rests on the premise that pavements and bases are effective in supporting loads chiefly because of the "surcharge effect" and, therefore, that the strength and weight of the surface and base layers must be designed to resist the potential upward thrust of the subgrade at points adjacent to, but outside, the area actually under load. This means that a load transferred through a layer of bituminous surface or crusher-run base may or may not be "spread" over the underlying layer or subgrade, but that the most important aspect is the tendency for particles in any layer to be displaced along a curved path (Fig. 1), and thus develop an upward thrust against the underside of the base or surface layer. This concept has been expressed by Rolan Vokack (Proceedings, Highway Research Board, 1943) and by Glossop and Golder in England.

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Pavements - Design

A New Approach for Pavement Design

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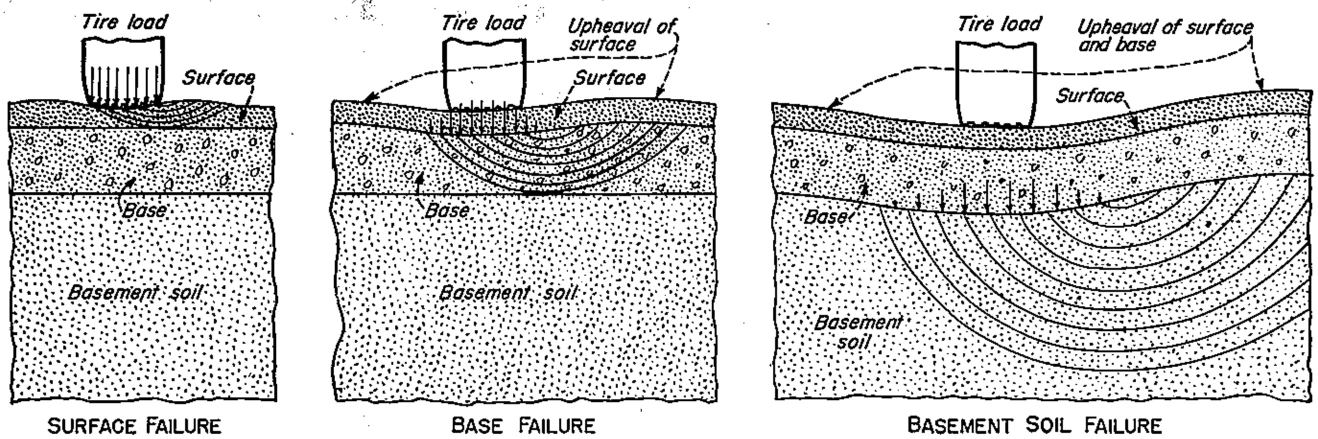

FIG. 1. TYPES OF FAILURE in pavements and bases studied in developing the design chart shown in Fig. 2.

A New Approach for Pavement Design

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A NEW METHOD for evaluating soils and calculating the thickness of pavement and pavement base required over any type of soil to support highway traffic or airplane wheel loads carried on pneumatic tires is under study by the California Division of Highways. A relatively simple design chart has been developed (Fig. 2) that makes use of certain physical characteristics of the basement soil and the pavement or pavement base as well as the surface loading. The theory on which the chart is based has been substantiated by results obtained on highway and airport test tracks.

This design procedure rests on the premise that pavements and bases are effective in supporting loads chiefly because of the "surcharge effect" and, therefore, that the strength and weight of the surface and base layers must be designed to resist the potential upward thrust of the subgrade at points adjacent to, but outside, the area actually under load. This means that a load transferred through a layer of bituminous surface or crusher-run base may or may not be "spread" over the underlying layer or subgrade, but that the most important aspect is the tendency for particles in any layer to be displaced along a curved path (Fig. 1), and thus develop an upward thrust against the underside of the base or surface layer. This concept has been expressed by Roland Vokac (*Proceedings*, Highway Research Board, 1943) and by Glossop and Golder in England.

Use of the design chart

The detailed procedure in applying the design chart is given in a box accompanying Fig. 2. However, the three factors used warrant fuller explanation. The first factor indicates the ability of the basement soil (or any imported layer) to resist displacement, and is designated as the "resistance value" R. This unit is a measure of the stability of the soil layer. It may be obtained directly from stabilometer tests by the expression

$$R = (1 - P_h/P_v)\ 100 \qquad (1$$

In this equation, P_h is the horizontal pressure and P_v the vertical pressure.

NOTATIONS

The symbols used in this article are defined as follows:

a = pavement area covered by pneumatic tire, sq. in

c = cohesiometer value of pavement or base (for rigid materials this value corresponds to modulus of rupture times 45.3)

CBR = California bearing ratio.

D = deforming effect of pneumatic tired wheel loads.

EWL = equivalent 5,000-lb. wheel loads

K = a constant that may vary from 0.0175 to 0.02 or more, depending on the factor of safety desired. Fig. 2 is drawn with K = 0.02.

P = pressure developed in the pavement by tire load, psi.

P_h = horizontal pressure; i.e., stabilometer reading, psi.

P_v = vertical pressure applied in the stabilometer test, psi.

r = number of wheel or axle load repetitions.

R = resistance value of the soil (range 0 to 100)

S - tensile strength of pavement or base.

T = thickness of all layers, including pavement, base, subbase, etc., above soil in question, inches.

The second factor used in this chart is the traffic index. This is a measure of the destructive values to which the pavement is subjected by traffic, and takes into account both the magnitude of the wheel loads and the number of times the loads are applied during the design life of the pavement (wheel load repetition).

The final factor recognized, the cohesion value c, indicates the tensile strength of the layers (pavement and/or base) that may be placed over the basement soil. This value is measured by a cohesiometer and for rigid materials has a linear relationship to the modulus of rupture.

When a stabilometer is not available, less elaborate testing or evaluation procedure can be substituted with some results being less accurate. Work done by D. J. Steele of the Public Roads Administration (*Proceedings*, Highway Research Board, 1945), provides a group index scale for classifying soils which shows a

HOW TO USE THIS CHART

With a straightedge intersect Scale A at the value for R given by Eq. (1) or some substitute method and Scale B at the traffic index for the total traffic load for the design life of the highway. The intersection of this line with Scale C is the thickness of gravel required to support the load (neglecting abrasion, etc.). From this point intersect Scale D at the cohesiometer value of the surface. This line will intersect Scale E at the thickness of base and surface required to resist plastic flow of the basement soil.

When the thickness of the surface material is to be less than one-half that indicated on Scale C, correct cohesiometer value for use on Scale D as follows:

$$S = \frac{\text{pavement thickness}}{0.5 \times \text{Scale C reading}} \times c$$

where:

S = corrected cohesiometer value
c = original cohesiometer value.

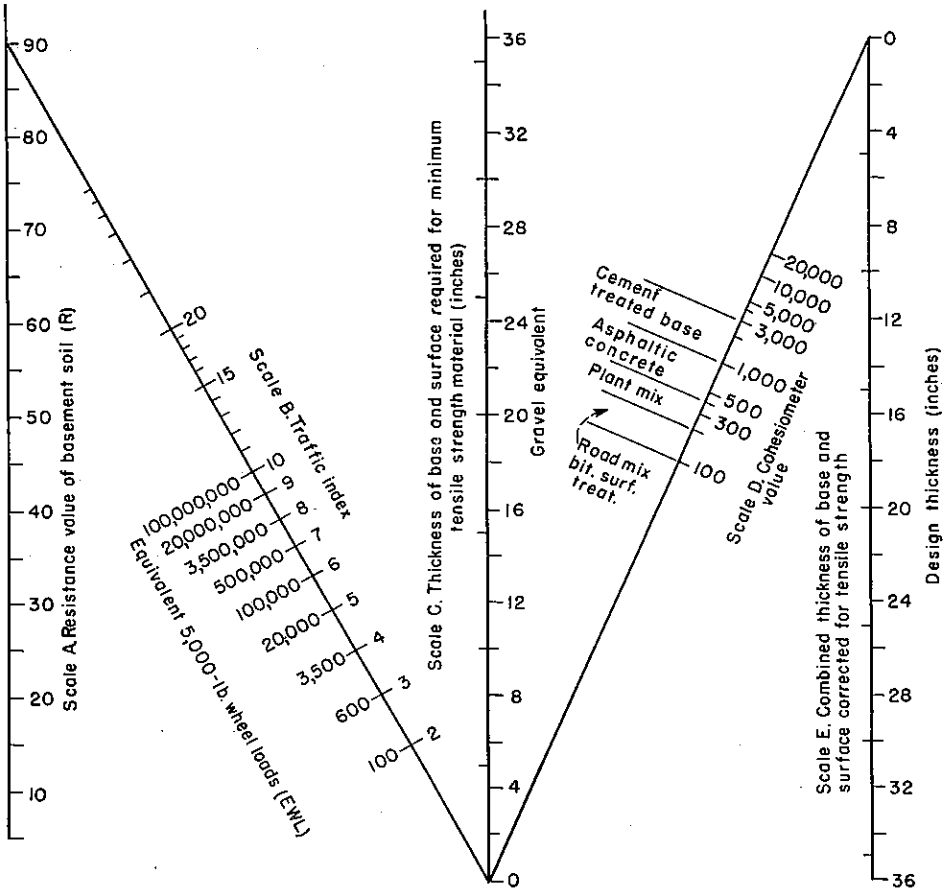

FIG. 2. DESIGN CHART used in the new design method to compute the thickness of compacted gravel with a light surface treatment or the equivalent thickness of base and pavement.

fair correspondence with the R value as derived from the stabilometer (Fig. 4).

In addition, in an unpublished communication, Mr. Steele has also suggested a relationship with the California bearing ratio (CBR) that when combined with the grading analysis and measured expansion, may also be used to give approximate values of R (Fig. 3). Either method for deriving R may be used in Fig. 2 for estimating the required thickness. It must be emphasized, however, that these alternate methods are not completely dependable or reliable for all materials.

Three factors related by formula

The over-all analysis of the problem indicates that there are three primary factors to be considered in designing the thickness of pavement capable of supporting traffic loads over the more or less plasticized mixtures of rock particles commonly called soil. First is the unit resistance R of the soil material over which the pavement or surfacing is to be constructed. This expresses the ability to resist plastic deformation. Second, is the accumulative destructive or deforming effect D of all the wheel loads that will pass over a given path on the pavement. This is the ability to produce plastic deformation. Third is the slab strength or tensile strength S of the pavement and base. This strength, in combination with the thickness of all layers above the soil in question, prevents the underlying soil from moving under the traffic.

These factors can be shown to have the following general relationship:

$$T = \frac{KD\ (90\text{-}R)}{S}$$

The resistance value as employed in this equation is primarily due to friction between the soil particles. The cohesive value or tensile strength in the soil layer is neglected because it cannot be relied upon any more than can the tensile strength of concrete in a reinforced beam. Material having a value of R greater than 90 would be capable of sustaining traffic without pavement cover except that it probably would lack the cohesive value or tensile strength needed to resist the abrasive action and thrust of the tires.

Fig. 2 is a graphical representation of the relationship between these values. In discussing the details of this formula and the corresponding chart, it is necessary to describe the basis for evaluating the three principal variables.

Soil resistance discussed

First is the question of soil resistance R. It has long been customary to speak of the supporting power or "bearing value" of soils and test procedures have been devised which are characterized as tests for "bearing value." It is well known by most engineers familiar with the behavior of soils and granular materials that the actual capacity to support loads varies considerably with the conditions of loading. Furthermore, the response of granular materials to different load areas varies widely, depending upon properties of the soil. Therefore, one of the tenets in the following discussion is to the effect

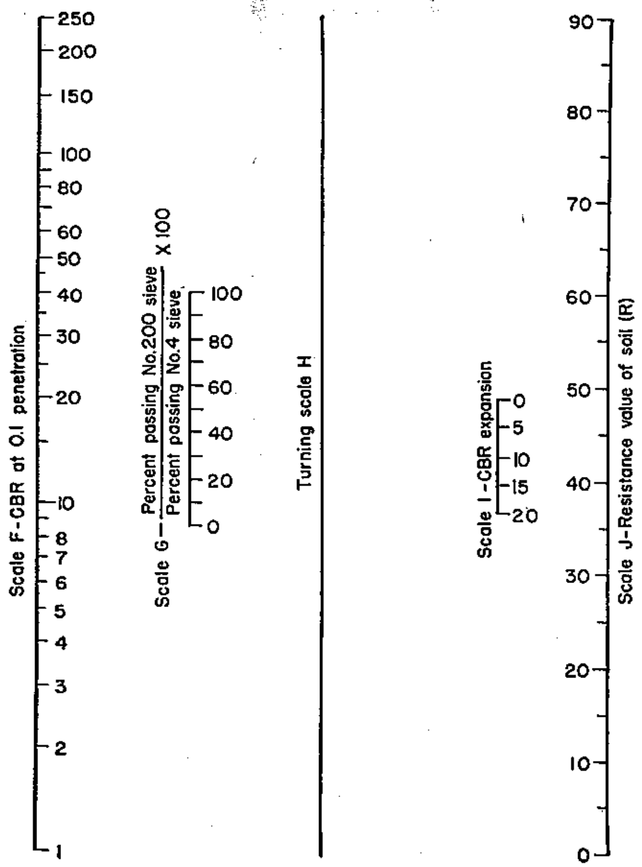

FIG. 3. WHERE TEST DATA or Stabilometer equipment are not available, a fairly reliable estimate of the resistance value may be obtained from California-bearing-ratio test results. This chart shows the relationship involved. However, it is not applicable for any material possessing all three of the following characteristics: (1) Less than 75 percent passing #4 sieve, (2) more than 8 percent passing #200 sieve, and (3) a product of the plasticity index and percent passing #200 sieve greater than 72.

that the term "bearing value" is not correctly applied to most soil strength test data and that the engineering properties of soils and granular materials can be more correctly evaluated in terms of internal resistance to deformation.

The usual approach attempts to analyze the load carrying capacity of granular materials through mathematical treatment based on the theory of elasticity. However the properties of such materials may be more easily understood by extending the principles of hydrostatics or by comparing the mechanics of soils to the behavior of liquids under pressure. It is, of course, axiomatic that one characteristic of a liquid is the ability to transmit pressure equally in all directions Masses of fine and coarse granular particles, particularly when combined with varying amounts of water, form combinations that will transmit some pressure in all directions, but not in a uniform pattern or to equal degree.

Therefore, if a sample of soil or granular material is placed in a cylinder and loaded under a tight-fitting piston, pressure will be transmitted to the sidewalls of the cylinder but the pressure thus transmitted can vary considerably. This variation depends upon the character of the soil particles and the amount of liquid combined with any clay or colloidal material. The whole relationship may be summarized by stating that the lateral pressure will vary inversely with the internal resistance of the mass. If a specimen of soil is prepared in the form of a cylinder and subjected to vertical loading with means for measuring the lateral pressure developed in the process, then the relative ability of a soil to transmit pressure may be indicated by the formula

$$\text{Lateral Thrust Ratio} = \frac{P_h}{P_v} \qquad (3)$$

The stabilometer furnishes a means for directly measuring the ratio between the vertical pressure applied to a test specimen and the lateral pressure transmitted by the material under load. For a stable roadway structure, the lateral support required, and also the resistance furnished by the base and surface, must be varied in direct proportion to the lateral pressure, as indicated by Eq. 3. It naturally follows that the capacity of a given layer of the soil to resist superimposed loads will be in inverse proportion to the above expression. Therefore, the resistance value of the material tested is indicated by Eq. 1.

Wheel load repetitions a factor

Next, it is necessary to establish a comparable means for evaluating the service loads or the potential tendency of pneumatic tired vehicle wheels to cause distortion or deformation. An examination of data developed on test tracks built by the California Division of Highways and on a track constructed by the Corps of Engineers at Stockton, Calif., indicates that, other things being equal, the minimum thickness or strength of the base and surfacing required to sustain traffic must increase directly as the logarithm of the axle load repetitions. This relationship has also been suggested by Norman McLeod of Canada.

From an examination of the markings on the pavement and the destruction produced it appears that the effect of moving vehicle wheels is comparable to a load applied on a strip the width of the tire and of a length varying with the speed of the vehicle. In addition, the width of a pneumatic tire print varies with the size of the tire, with the tire pressure, and with the load. Therefore, the potential deforming effect of loads carried on pneumatic tired wheels may be summarized by the expression

$$D = P\sqrt{a}\log r \qquad (4)$$

This equation agrees wth other formulas previously proposed, that indicate the thickness of cover varies according to the square root of the load.

To use this expression, all of the various axle loads must be counted or estimated and calculations made to determine the accumulated composite effect. An empirical approximation is secured by a simple method now in use by California Division of Highways. An estimate is made of the number of vehicles equipped with the various axle combinations. To this is applied an aribtrary set of constants that have been assigned to represent the relative destructive effect of the various wheel load groups. These constants are given in Table I.

The number of axle loads in each group is estimated as accurately as possible, preferably from traffic census and loadometer data, and the number of loads per year in each group is multiplied by the assigned factor. The products are added and multiplied by the number of years contemplated as a basis for the design life of the pavement.

For example, traffic census on a given highway indicates a total of 22,737,456 vehicles in ten years. Of this number, the heavy traffic may be classified into wheel load groups, use percentages applied, and the equivalent 5,000-lb wheel loads computed as shown in Table II.

Results of computations similar to Table II obviously will not correspond to computed values derived from the formula proposed to express the destructive effect of traffic (Eq. 4). However, all attempts to estimate traffic for the future on any highway must be subject to so many imponderables that one is not inclined to engage in hair splitting as long as the relative values used are reasonably correct. Accordingly, Eq. 4 was modified and Fig. 2 developed on the basis of the following:

$$T = \frac{0.12 \log \text{EWL}\,(90-R)}{\sqrt[5]{c}} \qquad (5$$

(In this equation, $\sqrt[5]{c}$ has been substituted for S as this term has been established empirically to express the tensile strength of the pavement and/or the base.)

Equivalent "gravel" thickness

Neglecting the pavement-strength factor for the moment, it is now possible to compute the thickness of gravel or granular material that, by its weight alone, will counteract any tendency of the underlying basement soil to be displaced and thrust upward as a result of vehicle loads.

In pursuing this theory of design, it becomes evident that the internal stability or resistance value of any granular sub-base or base course will have little influence on the thickness required so far as protecting the underlying soil is concerned. (Provided, of course, that the base material has sufficient sand or fines to prevent infiltration of a clay soil). In other words, there will be little or no difference between the thickness of clean sand, gravel, crushed stone or any combination of materials that resists displacement of the subgrade simply by means of the weight of the superimposed layers. This latter conclusion may be somewhat surprising to some, but the evidence appears to be ample and, when viewed in the light of the theoretical premises, there is no reason for any difference. This viewpoint has already been expressed by Spangler and Vokac and recently supported by McLeod.

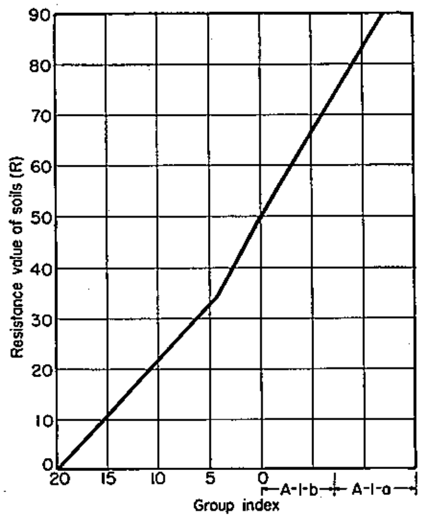

FIG. 4. ANOTHER APPROXIMATION for the resistance value is available through use of a group index classification developed by D. J. Steele of the Public Roads Administration.

On the other hand, it has long been known that a lesser thickness of pavement is required provided the pavement has some definite flexural strength or slab strength. For example, a plank has substantial supporting power when placed on soft mud or swampy ground, while a layer of bricks would soon sink out of sight.

In order to estimate the reduction in total thickness made possible through the use of a strong pavement or base, it is necessary to make an allowance for the one distinctive property these materials possess; namely, tensile strength or cohesive strength. It is evident from the examination of test track data that, other things being equal, the ability to support traffic increases as some function of the tensile strength. The slab strength of rigid materials, such as portland-cement concrete or cement-stabilized base mixtures, can be indicated by flexural strength tests and the modulus of rupture.

Although the modulus of rupture concept is not readily applicable to such yielding or ductile materials as bituminous pavements; such materials do possess measurable tensile strength, especially under rapidly applied loads. This strength can be evaluated by means of the cohesiometer, an apparatus capable of breaking small beams of bituminous mixtures in tension. By using a controlled rate of load application, the tensile strength or modulus-of-rupture values for compacted bituminous mixtures and rigidly cemented mixtures may be compared in the same scale.

This arrangement is purely arbitrary and holds good only as long as a certain normal range of traffic speed

TABLE I — CONSTANTS USED TO REPRESENT DESTRUCTIVE EFFECT OF TRAFFIC.

Wheel Load (lb.)	Factor
4,500 to 5,500	1
5,500 to 6,500	2
6,500 to 7,500	4
7,500 to 8,500	8
8,500 to 9,500	16
9,500 and over	32

TABLE II—METHOD OF COMPUTING EQUIVALENT WHEELS LOADS (EWL).

(1) Wheel Load Groups	(2) Percent of total Vehicles	(3) Number of Vehicles	(4) Factor	(5) EWL (3) x (4)
4,500–5,500	10.71	2,435,000	1	3,435,000
5,500–6,500	9.61	2,185,000	2	4,370,000
6,500–7,500	11.96	2,719,000	4	10,878,000
7,500–8,500	6.02	1,369,000	8	10,950,000
8,500–9,500	3.40	773,000	16	12,369,000
9,500 and over	0.91	207,000	32	6,621,000
Total equivalent wheel load in 10 years				47,623,000
Design repetitions (traffic in one direction)				23,812,000

Tables I and II are from *California Highways and Public Works*, March, 1942.

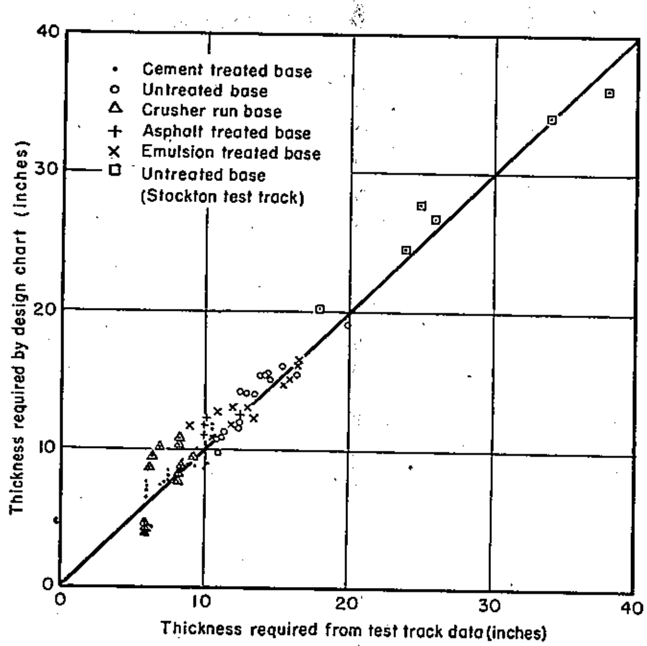

FIG. 5. PAVEMENT DESIGN calculated from Fig. 2 and thicknesses developed in the course of test track experiments show a correlation.

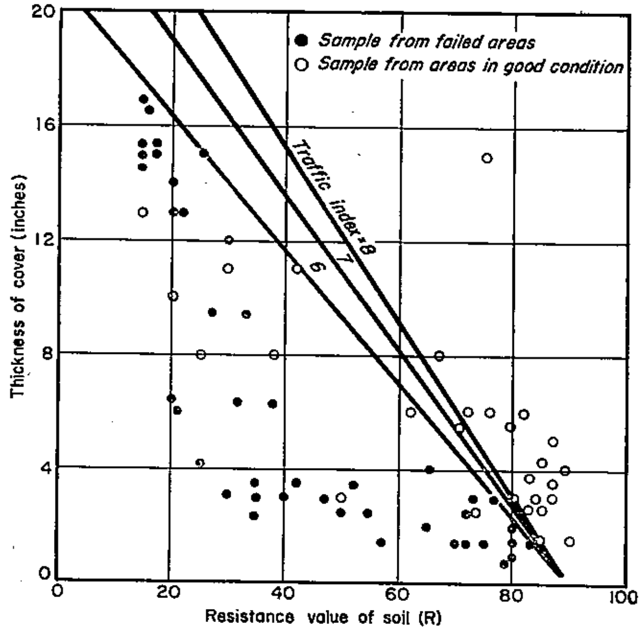

FIG. 6. A RELATION between some of the factors used in Fig. 2 and scattered samples from existing highways is shown by this chart.

is considered. For extremely slow speeds or for standing loads, the values assigned for the tensile strength of bituminous pavements should be reduced, while on the other hand, the values could be substantially increased for very high speed traffic or for colder climates.

In any event, with increasing slab strength the total thickness of base and surface may be reduced below the amount required for uncemented granular materials alone and the magnitude of this correction is indicated by Scale D on Fig. 2. The entire relationship is indicated by the formula

$$T = \frac{K\ (P_h/P_v\text{-}0.10)\ (P\ \sqrt{a}\ \log r)}{\sqrt[5]{c}} \qquad (6)$$

It is well known that soils are fairly complex mixtures of organic and inorganic materials with varying amounts of water always included. Such complexity is illustrated by a report listing the essential details of 22 proposed methods all different, for calculating the thickness of base and surface required over various types of soil (*Proceedings*, Highway Research Board, 1945).

A current AASHO committee, engaged in the preparation of a construction manual, have stated that "as yet no mathematical formula has been developed on a theoretical basis which can be depended upon to give the thickness of layer which is required to serve satisfactorily." The same statement could also apply to empirical methods. Thus, the procedure proposed herewith is one more in a long list of attempts to provide a solution to a vexing problem.

Not a panacea for pavement ills

While it is believed that Fig. 2 includes all essential factors influencing the thickness and strength requirements for pavements and base materials, it is not claimed to cure all weaknesses and shortcomings which may develop in pavements or roadway surfaces. Pavements can fail not only because of inadequate thickness or strength or because of a poor subgrade, but also from causes inherent in the composition of the pavement materials.

For example, bituminous pavements may be unstable or may disintegrate due to the action of water or because of improper mixture design. Concrete pavements have disintegrated due to freezing and thawing or to the action of salts attacking the pavement. Also, they may deteriorate through destructive reaction between alkali in the cement and certain types of aggregates. Further, portland-cement concrete pavement joint troubles are not cured by increasing the slab thickness.

Increasing the depth of the base or sub-base will not correct troubles arising from the fact that the base material itself is unstable. Therefore, it should be clearly understood that the foregoing outline deals only with those problems of paving design that can be solved by providing a pavement and base of adequate thickness or slab strength.

It must be further pointed out that pavements may fail or at least may develop extensive cracking over soils that have excessive resilience or ability to rebound after loading. There are many examples to be observed where badly cracked pavements have not distorted appreciably. Certain resilient or "springy" soils will support traffic loads without permanent displacement. In such cases, it is evident that the foundation is sufficiently deflected under the passing of each load to cause extensive cracking of any rigid pavement whether concrete or of some bituminous type.

Use of stabilometer

The foregoing discussion rests upon the belief that the resistance of a soil to plastic deformation may be determined most simply and directly by means of the stabilometer. It should, however, be emphasized that this test is not applied according to prevailing notions surrounding the determination of angle of friction and cohesion by the triaxial shear method.

The triaxial shear test as commonly performed requires a specimen in which the height is at least two and one-half times the diameter and, in the process of testing, loads are applied until "failure" is indicated against some arbitrary preestablished lateral pressure. In the stabilometer test no attempt is made to establish any so-called failure point as it seems that the term "failure" is a rather vague and elusive concept when applied to the distortion of either plastic clays or cohesionless sands.

The stabilometer is used to determine the ratio between vertical pressure P_v and horizontal pressure P_h. When expressed as the ratio $(1-P_h/P_v)$x100, it furnishes values in a linear scale reflecting that portion of the soil resistance resulting primarily from friction between the particles under the conditions of lubrication existing in the test specimen.

Reproducing road conditions

It is important that the material be tested in the most unfavorable condition that may be expected to develop in the road-bed during the life of the project. Applying this principle means that the sample should be compacted, degraded, and combined with an amount of moisture to correspond to the worst conditions expected in service. This principle includes the possibility that under certain conditions, the use of relatively dry samples might be justified. However, in the absence of definite knowledge to the contrary, all soil materials should be tested at saturation and should represent both the kind of compaction and the degree of density that can be obtained and maintained after the material is in place on the road.

Excepting frost action, the ultimate equilibrium condition for a given soil depends upon the swelling characteristics of the soil and the weight of the layers of base and surface material with which it is to be covered. The moisture content of the soil when tested should correspond to its moisture content after readjustment and expansion in the roadbed. To predict the future capacity for moisture, it is necessary to measure the capacity of the soil while under load to expand or swell due to water actions. An apparatus has been devised for measuring the expansion pressure. The expansive force is measured on several trial specimens compacted to different degrees and saturated. The resistance value is then measured by the stabilometer. By means of intersecting curves, these two values are reconciled to indicate the most economical thickness of cover material that will satisfy both considerations.

Other methods of estimating R

Where stabilometer and an adequate compaction device are not available, some less elaborate testing or evaluation procedure is desirable. A considerable amount of work has been carried out by various agencies throughout the years on an entirely different approach to the problem, namely, seeking to evaluate the soils by means of soil classification schemes. Such classifications have been developed by the Public Roads Administration, Civil Aeronautics Agency, and the Corps of Engineers. Most of these classification schemes are not directly or reliably translatable into the supporting power of the soil.

D. J. Steele of the Public Roads Administration has outlined a method for establishing a soils group classification for design purposes (*Proceedings*, Highway Research Board, 1945). Steele's group classification is based upon the Atterburg limits and the grading analysis. It appears that a fairly good correlation exists between this classification and the soil resistance values measured in the stabilometer. Fig. 4 indicates the approximate relation between the group index and the *R* value.

By use of another procedure suggested by Mr. Steele, *R* values may be derived from CBR test data. This involves (a) certain limitations on the type of material tested, (b) correction for the amount of expansion developed during the soaking period and (c) correction for the amount of material passing a No. 200 sieve. Fig. 3 indicates the manner in which test results from the CBR apparatus may be converted into the equivalent resistance values. This chart should not be used for any material possessing all three of the following characteristics: (1) Less than 75 percent passing #4 sieve, (2) more than 8 percent passing #200 sieve, and (3) the product of the plasticity index and percent passing #200 sieve greater than 72. This conversion appears to have fair correlation for most materials other than those specifically excepted.

Fig. 5 indicates the degree of correlation between the thicknesses indicated by Eq. 6 and the actual minimum thickness that gave satisfactory results on the test tracks. Best agreement between the data and the formula is achieved by the value of $K = .0175$. However, in preparing Fig. 2 the value of *K* was increased to 0.02 to place all calculated thicknesses on the safe side. Fig. 6 indicates the relationship between the values of *R* and actual performance as indicated by scattered samples taken from existing highways.

Method under study

The procedure outlined in the foregoing, using Fig. 2 and Fig. 3, is now being put into use on a trial basis for flexible pavement design by the California Division of Highways. It is not unlikely that certain modifications or revisions will be indicated as experience is accumulated.

It must be pointed out, however, that the inevitable variations in soils and all naturally occurring granular materials will always tend to offset any extreme refinement or precision in applying a design formula. There are limits to the control which may be exercised during construction. There is a question whether it will be possible to realize any practical benefits from further refinements in the method.

The writer wishes to acknowledge the contributions of the many individuals and organizations who have made it possible to develop the pavement design procedure outlined in the foregoing. The work was done in the Laboratory of the California Division of Highways under G. T. McCoy, state highway engineer, and T. E. Stanton, materials and research engineer. The necessary test data were obtained from two test tracks constructed by the Division of Highways and one by the Corps of Engineers at Stockton, Calif. Much credit is due Robert Carmany, who developed most of the mathematical relationships, and Ernest Zube, who was in charge of the testing and recording of observations on the test track. D. J. Steele and Walter Liddle of the Public Roads Administration gave much valuable assistance and advice.